COPEIA

1995, No. 4 December 21

Copeia, 1995(4), pp. 773–779

Effects of Turtle Excluder Devices (TEDs) on Loggerhead Sea Turtle Strandings with Implications for Conservation

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All five species of sea turtles in United States waters are listed under the Endangered Species Act as threatened or endangered. A major source of mortality for these turtles is drowning in shrimp trawls; 70–80% of strandings of dead turtles on beaches are related to interactions with this fishery. In the late 1980s, the state and federal governments began requiring turtle excluder devices (TEDs) in trawl nets; TEDs allow turtles to escape the nets before they drown. To date, the effectiveness of TEDs in reducing sea turtle strandings has not been quantitatively assessed. In this paper, we report on a statistical analysis of strandings data for loggerhead sea turtles on South Carolina beaches from 1980–1993. These data are long term, based on excellent beach coverage and include eight years before TEDs were required, two years of intermittent use, and four years with TED regulations in place. Regression analysis of the natural log-transformed strandings data showed a good fit to the model ($R^2 = 0.88$). The model had significant linear and squared trend terms suggesting the trawlers were sampling from a declining population (−5.3% per year), but the rate of decline has diminished. The analysis shows significant effects of the shrimp fishery in increasing strandings. The effect of TEDs in reducing strandings was also significant; TEDs reduce strandings by about 44% relative to the estimated effects of shrimp trawls without TEDs. If reductions in stage-specific mortality rates are at all similar to the observed reductions in strandings due to TEDs and other mortality sources do not intervene, population model predictions suggest that the outlook for loggerhead population recovery is good.

THE loggerhead turtle, *Caretta caretta* was listed as a threatened species pursuant to the Endangered Species Act in 1978. Sea turtles can die at sea from a variety of natural and anthropogenic factors, but the extent of mortality in the marine environment is difficult to assess and has gone largely undocumented (National Research Council, 1990). Natural factors include disease and predation. Human-made factors include boat collisions, entanglement, and incidental capture by various fisheries. When decomposition occurs, internal gases float carcasses, and prevailing winds or nearshore currents bring some of them ashore. An unknown number never reach shore because they are eaten by scavengers or break apart and sink. Nevertheless, strandings (i.e., the dead turtles that wash ashore) are a useful tool to gain life-history information and to provide managers with information upon which to base regulatory actions for fisheries that impact these listed species (National Research Council, 1990).

The problem of stranded sea turtles appearing on beaches of the southeastern United States in relation to the activities of the shrimp fleet was first documented in the early 1970s (Talbert et al., 1980; G. F. Ulrich, 1978, unpubl.; T. M. Murphy and S. R. Hopkins-Murphy, 1989, unpubl.). To standardize data on stranded sea turtles, a regionwide Sea Turtle Stranding and Salvage Network (STSSN) was established in 1980 by the National Marine Fisheries Service (NMFS) in cooperation with state, federal, and privately operated turtle projects and volunteers.

Concurrently, concern over the extent and impact of incidental catch mortality by the shrimping fleet led to the quantification of capture levels (Bullis and Drummond, 1978; H. O. Hillestad, J. I. Richardson, and G. K. Williamson, 1977, unpubl.). Henwood and Stuntz (1987) gathered all available data on sea turtle capture and mortality rates in shrimp trawls and estimated that 11,000 turtles were killed annually. In the same year, a loggerhead population model was published (Crouse et al., 1987); sensitivity analysis and simulations of various management scenarios showed that mortality in large juvenile and subadult turtles had a large effect on population growth rates. These are also the size classes most frequently observed among stranded individuals.

T. M. Murphy and S. R. Hopkins-Murphy (1989, unpubl.) clearly established the relationship between sea turtle mortality and shrimping operations. More recently, the Committee on Sea Turtle Conservation of the National Research Council reviewed scientific and technical information pertaining to the conservation of sea turtles and the causes and significance of turtle mortality, including that caused by commercial trawling, and concluded that trawling was the single largest anthropogenic source of mortality (National Research Council, 1990).

During the 1980s, the NMFS tested various types of gear that would release sea turtles from trawls (termed Turtle Excluder Devices or TEDs). Dissatisfaction with the NMFS design led some shrimpers to invent smaller and lighter TEDs. Some trawlers in Georgia were using TEDs to exclude jellyballs (*Stomolophus meleagris*) as early as the mid-1980s.

Also during the 1980s, South Carolina conducted statewide aerial beach surveys to monitor the nesting population of loggerhead turtles (1980–1982 and 1985–1987). Between these two monitoring periods, a decline of more than 26% occurred in the nesting population (Hopkins-Murphy and Murphy, 1988). The declines documented were coastwide and involved both developed and undeveloped beaches. The declines were not attributable to anything related to the quality or quantity of the nesting habitat (Hopkins-Murphy and Murphy, 1988).

Based on this information, the South Carolina Wildlife and Marine Resources Commission passed emergency regulations, and in 1988, South Carolina became the first state to require TEDs in shrimp trawls during May through Aug. The regulations were challenged but upheld several times in court that summer. A similar scenario occurred in 1989 with the federal regulations. By 1990, both state and federal TED regulations were in effect, and in South Carolina, compliance was good. The empirical data suggested that TEDs could reduce trawling-related mortality, and the loggerhead model suggested that reductions in mortality in the affected stages could have substantial positive effects on loggerhead recovery (Crowder et al., 1994).

The questions we address here are, first, can we document statistically significant effects of the shrimp fishery on strandings? Second, do TED regulations lead to a significant reduction in strandings? And finally, can we estimate the magnitude of those effects and use the loggerhead population model (Crowder et al., 1994) to determine their implications for loggerhead recovery? We approach these questions by examining the time series of loggerhead strandings relative to shrimp fisheries in South Carolina. The problem has been addressed throughout the southeastern United States, but the data from South Carolina provide one of the longest term, highest quality records.

Methods

Field sampling.—South Carolina beaches were monitored on the ground or by aerial survey. Reports of dead turtles from the public were referred to the network member assigned that particular beach. Standardized data forms were used by all members of the network, and data on strandings were sent to a state coordinator for checking. Each state coordinator then sent copies of the data forms to the NMFS Southeast Fisheries Science Center in Miami, Florida, to be archived and summarized for quarterly, semiannual, and yearly reports.

Approximately 50% of the 35 beaches and islands in South Carolina were surveyed in 1980, as the network was being established, and approximately 90% were surveyed in subsequent years. Because effort and quality control were both consistent and high during the sampling period, we assumed effort was constant within and among years in reporting the strandings data.

Data recorded on each stranded carcass included the following: observer's name, address and phone number, stranding date, species, turtle number by day (if more than one carcass was recorded on the same day), reliability of identification, whether the species identification was verified by the state coordinator, sex, location, condition of the carcass (i.e., decomposition state), tag numbers (if present), final disposition of the carcass, and any remarks the observer wanted to add. There was also a diagram of a sea turtle on the form where injuries or missing flippers could be noted. Curved carapace length was taken from the nuchal notch to the posterior marginal tip. Curved carapace width was taken at the widest part of the shell.

The subadult size classes included all sizes below 76 cm. Any individuals above 76 cm were considered to be adult. All animals were either painted, buried, or removed from the beach to ensure that none were counted twice.

Statistical analyses.—We performed regression analysis of numbers of turtles stranded per biweekly period from data collected on South Carolina beaches from 1980–1993 (see Appendix). This included an eight-year period without TEDs (1980–1987), two years (1988–1989) of intermittent TED use as state and later federal regulations requiring TEDs were implemented. Finally, TEDs were required in both state and federal waters beginning in 1990, so this analysis includes four years of data with TED regulations in place.

Because the errors in the statistical model were correlated, we fit a time-series model to the residuals to estimate standard errors of the regression parameters (see Appendix). One problem with applying these analyses is that the years are incomplete. The period from Dec. to March each year was not sampled. Strandings are highly unlikely during this period due to lack of turtles in the area (VanDolah and Maier, 1993) or lack of mortality sources over winter. For the purposes of analysis, then, we defined the year to be April–Nov. During the first two years TEDs were required (1988–1989), they were in effect sporadically due to challenges in the courts. This can make it more difficult to detect TED effects because turtles that strand during a TED period may actually have been caught in a net not equipped with a TED in the previous biweekly interval. We assumed that, during the biweekly periods when TEDs were required, compliance with the regulations was good; significant lack of compliance, again, could make it difficult for TEDs to have much of an effect on strandings.

The model includes linear and squared trend terms to capture the overall trend in declining loggerhead numbers (see Appendix) and also includes three sinusoidal terms to represent frequencies of one, two, or three cycles per year. Additional variables encode whether shrimping season was in progress or not and whether TED regulations were in effect or not for each biweekly period. The shrimping season generally started between 15 May and 15 June each year, although later starting dates have occurred. For this analysis, we assumed the season ended 31 Oct. because, although shrimping effort continues until late Dec. or early Jan., sea turtles leave coastal areas as water temperatures decline. A measure of shrimping effort did not improve the model because most of the strandings occur early in the shrimping season independent of effort later in the season. Additional details of the regression model and analysis are available elsewhere (Appendix; Royle and Crowder, 1994).

The statistical model allows us to estimate an overall trend in the number of loggerheads stranded, any oscillatory fluctuations in the data, the effect of shrimping on strandings, and the effect of TEDs in reducing strandings during the shrimping season. Parameters were considered significant in the regression model if $P < 0.05$.

Results

Numbers of loggerheads reported stranded on South Carolina beaches have generally declined since the early 1980s (Table 1). There appears to be a strong periodic behavior in numbers of stranded loggerhead turtles; some years include an early spring mode, followed by a larger mode (Fig. 1). This early spring mode was most apparent early in the record (1980–1982) when sea turtles were incidentally caught in gill nets set for Atlantic sturgeon. In 1983–1985, the sturgeon season was closed in mid-April to minimize interactions with turtles; in 1986, gill netting for sturgeon ended due to depletion of the sturgeon stock. The large mode in late spring/early summer has been interpreted as shrimping-related (National Research Council, 1990; T. M. Murphy and S. R. Hopkins-Murphy, 1989, unpubl.) and often correlates closely with the onset of shrimping in nearshore waters. After the initiation of South Carolina TED regulations in 1988, numbers of strandings appeared to decline. But the loggerhead nesting population in the region was also declining at about 5% per year (Hopkins-Murphy and Murphy, 1988), so one has to separate the apparent reduction in number of turtles stranded from declines underway in the population from which turtles were being removed by the fishery.

The statistical model provides a good fit to the natural log-transformed data (Fig. 2); and plots of the residuals showed the transformation effectively stabilized the variance, and the residuals were normally distributed. A first-order moving-average model (see Appendix) appeared to be sufficient; the residuals from the model showed no significant autocorrelation (Box-Pierce Q-statistic, $Q = 6.20$, 11 df, $P = 0.860$). The log transformation provided normally distributed data required for valid hypothesis tests (Anderson-Darling Goodness-of-

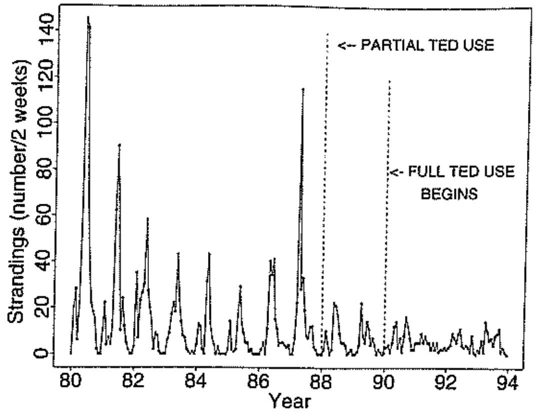

Fig. 1. Numbers of loggerhead sea turtles stranded on South Carolina Beaches per biweekly period from 1980–1993. Turtle excluder devices were first required in 1988 in state waters (0–3 miles) and in 1989 in federal waters (offshore of 3 miles). Full TED use began in 1990.

Fit test; Stephens, 1976; $A^2 = 0.405$, $\alpha = 0.10$). The overall R^2 for this model was 0.88, indicating that 88% of the variation in these data are explained by the model.

The overall trend in strandings has significant linear and squared components on the log scale (Appendix, Table 2). It may be useful to estimate some "average rate of decline" over the 1980–1993 period. We did this by refitting the model without the squared term and produced an estimate of −5.3% per year, which is similar to the magnitude of the population decline noted in aerial surveys of nesting females (Hopkins-Murphy and Murphy, 1988). The quadratic nature of the trend suggests the rate of decline in strandings is diminishing.

The data also have significant periodicity with 1, 2, or 3 peaks per year (Table 2). The model specifically addressed the effects of the shrimp fishery, which significantly increased strandings. The TED parameter estimate was also significant. If we estimate the magnitude of this effect on the linear scale, the estimate of the TED effect is −16 turtles per biweekly period. The shrimping effect is about +36 turtles per period. Thus, our results suggest that strandings when TEDS were in use were about 20 turtles per biweekly period or 44% less than when TEDS were not in use but shrimping was underway (Royle and Crowder, 1994).

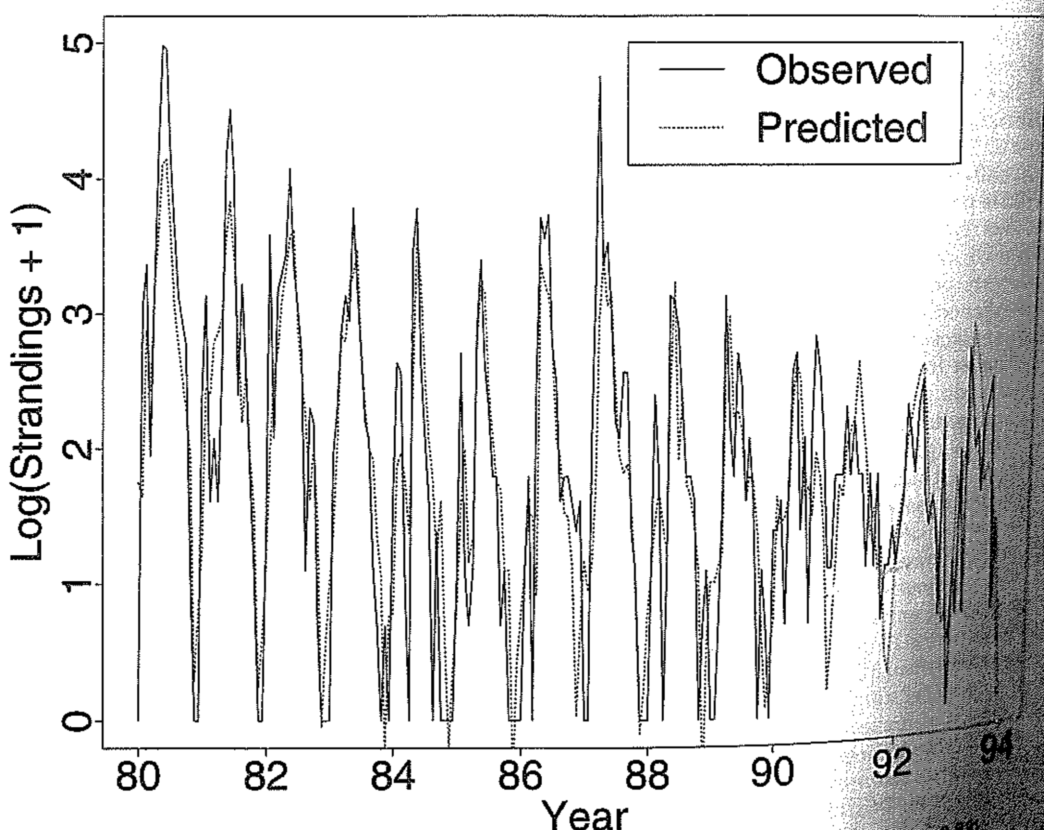

Fig. 2. Fit of the time series regression model to the natural log-transformed data ($R^2 = 0.88$).

TABLE 1. BIWEEKLY LOGGERHEAD STRANDINGS. Dates are those at the beginning of the period.

Year	4-1	4-16	5-1	5-16	6-1	6-16	7-1	7-16	8-1	8-16	9-1	9-16	10-1	10-16	11-1	11-16	Total
1980	0	20	28	6	22	64	145	141	67	37	22	18	15	2	0	0	587
1981	10	22	4	7	4	12	62	90	55	10	24	12	5	2	0	0	319
1982	3	35	7	23	26	30	58	27	20	14	2	9	8	1	0	0	263
1983	0	6	9	17	22	18	43	23	14	8	7	2	1	0	1	0	171
1984	4	13	12	2	0	31	43	13	7	4	0	3	0	0	0	0	132
1985	2	14	2	1	2	17	29	13	9	5	5	1	2	0	0	0	102
1986	0	2	5	0	11	40	34	41	15	11	4	5	5	4	3	4	184
1987	0	0	7	22	115	28	33	19	8	7	12	12	3	2	0	0	268
1988	0	2	10	5	0	2	22	21	17	9	5	5	4	0	1	2	105
1989	0	0	1	4	22	8	5	14	11	4	7	4	0	2	1	0	83
1990	3	3	4	1	5	12	14	3	7	1	8	16	12	7	2	2	100
1991	5	5	5	9	5	8	5	5	2	5	2	5	1	2	2	3	69
1992	2	3	4	9	7	5	9	11	4	3	4	3	1	8	1	0	74
1993	2	1	6	1	14	10	6	7	4	8	9	11	1	3	1	0	84

DISCUSSION

Our analysis of the South Carolina strandings data show conclusively that shrimp trawling was historically correlated with increased strandings of loggerhead sea turtles. The recent declines in strandings reflect a declining population at about 5.3% per year which is similar to the estimate of declines in adult nesting females from aerial survey data in South Carolina (Hopkins-Murphy and Murphy, 1988). But the trend data also had a significant squared term which suggests that the rate of decline in loggerhead strandings has diminished. This parallels recent findings from aerial surveys of nesting females completed in 1990–1992 (Hopkins-Murphy and Murphy, 1994). Apparently, the rate of population decline has been reduced for nesting females. Finally, our analysis documents a significant effect of TEDs in reducing strandings.

A recent update of the loggerhead population model (Crowder et al., 1994) used two techniques to estimate the effect of TEDs in reducing mortality of large juveniles, subadults, and adults. The first compared differences in survival of these stages in an unexploited loggerhead population from Australia (C. Limpus, unpubl. data) to that estimated from Little Cumberland Island, Georgia, before TEDs were required. This difference was then scaled by the expected effects of TEDs on reducing trawling-related mortality (Henwood et al., 1992). The population projection for trawling-related mortality due to "seasonal offshore" TED regulations beginning in 1988 suggested a reduction of total mortality (in vulnerable stages) of about 35%. Crowder et al. (1994) also estimated the effects of TEDs from a simple linear regression of the South Carolina annual strandings data for 1980–1987 (before TEDs) relative to actual strandings in 1990–1991 (with TEDs). This estimate was a mean reduction in annual strandings of 37%. In this paper, analyses using a regression model with time series errors based on biweekly reporting periods and including data through 1993 suggests a 44% reduction in strandings related to TED use. Based on simulations of the loggerhead population model (Crowder et al., 1994), a reduction in mortality rates of this magnitude for stage classes affected by TEDS would allow the loggerhead population to grow by an order of magnitude over the next 55–60 yr.

Maintenance of long-term data to determine population trends will be required for long-lived threatened and endangered species like sea turtles. Because stranded turtles include large ju-

TABLE 2. ESTIMATES OF REGRESSION PARAMETERS, MA(1) PARAMETER, AND STANDARD ERRORS FROM MODEL 1 FIT TO LOG (STRANDINGS + 1).

Parameter	Estimate	Standard error	t-Value	P-Value
β_1	3.0071	0.20456	14.70	.0001
β_2	1.9706	0.24680	7.98	.0001
β_3	−0.5764	0.21436	−2.69	.0040
A_1	−0.6961	0.13537	−5.14	.0001
B_1	0.5586	0.11436	4.88	.0001
A_2	0.0431	0.08822	0.49	.3130
B_2	0.1599	0.09356	1.71	.0900
A_3	−0.2000	0.07955	−2.51	.0070
B_3	0.1696	0.07942	2.14	.0200
θ_1	−0.0147	0.00401	−3.66	.0001
θ_1	5.64e-5	1.81e-5	3.12	.0010
ρ	0.3556	0.06542	−5.44	.0001

veniles and subadults as well as adults, we may expect to detect a TED effect more rapidly in strandings data than in data on the abundance of nesting females. Changes in the size structure of the loggerhead population may be expected with TEDs (Crowder et al., 1994); this too may be detectable in strandings data. Long-term monitoring data on nesting beaches and of strandings will continue to be useful to evaluate management options such as TED regulations and to evaluate predictions of population responses.

It is now evident that sea turtle strandings are related to trawling activity and that TEDs can reduce this effect substantially. Although data from other states have not been thoroughly analyzed, the compiled data from the national Sea Turtle Stranding and Salvage Network (B. Schroeder, unpubl.) for three years before federal regulations (1986–1988) averaged 33% higher than the average for three years with TEDs (1991–1993) (D. T. Crouse, L. B. Crowder, and S. S. Heppell, unpubl.). This suggests that TEDs are working both in South Carolina and regionally to reduce strandings. If reductions in stage-specific mortality rates are at all similar to reductions in strandings and other sources of mortality (e.g., bycatch in longline or other fisheries) do not intervene, the outlook for loggerhead recovery is excellent (Crowder et al., 1994).

Acknowledgments

The stranding network in South Carolina is supported by NOAA/NMFS funding under Section 6 of the Endangered Species Act. We thank the many members of the network who have given of their time over the years. The statistical analysis and modeling portion of this work was supported by NOAA/NMFS and UNC Sea Grant (R/MER-21 and NOAA/NMFS NA90AA-D-S6847). We thank D. Crouse, S. Heppell, T. Murphy, K. Rose, N. Thompson, and B. Wenner for sharing insights and commenting on this manuscript.

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APPENDIX

We performed a regression analysis on the biweekly turtle stranding counts for the period 1980–1993. Analysis of the residuals from this model indicated violation of the assumptions of constant error variance, and independence of the errors. A log transformation of the dependent variable and a simple time-series model fit to the errors corrected both of these problems. In this Appendix, details of the particular regression model are given, followed by explanation of the model fitting and assumption verification. Additional details of the analysis are available in Royle and Crowder (1994).

Initially, the following regression model, which incorporates major effects evident in the data, was used to model turtle strandings:

$$Y_t = \beta_1 X_{1t} + \beta_2 X_{2t} + \beta_3 X_{3t} + \sum_{i=1}^{3} A_i \cos(2\pi\omega_i t) + \sum_{i=1}^{3} B_i \sin(2\pi\omega_i t) + \theta_1 t + \theta_2 t^2 + \epsilon_t.$$

Here, Y_t is the number of strandings in biweekly period t, and the ϵ_t are assumed independent and normally distributed with mean zero and constant variance. The parameters that must be estimated are the coefficients A_i and B_i, the trend parameters θ_1, θ_2, the on-season and off-season mean strandings β_1 and β_2 and the TED effect, β_3. Note that this model is parameterized without a constant mean. Here the two indicator variables X_{1t} and X_{2t} added together take the place of an overall constant and are defined as follows: $X_{1t} = 1$ if shrimp season was open during period t, 0 if shrimp season was closed during period t; $X_{2t} = 0$ if shrimp season was open during period t, 1 if shrimp season was closed during period t. The TED effect variable, X_{3t} is defined similarly as $X_{3t} = 1$ if TED use was required for period t, 0 if TED use was not required for period t.

This indicator parameterization is simple and easy to interpret. In the absence of other effects in the model, the expected number of strandings on-season with no TEDs is β_1, the expected number of strandings off-season is β_2, and the expected number of strandings on-season with TEDs is $\beta_1 + \beta_3$. Here, β_3 is the TED effect; and if TEDs have the effect of reducing strandings, we would expect to see a negative estimate of this quantity.

An estimate of the TED effect based on the simple mean between the number of strandings during off-TED periods and TED periods is essentially this estimate unadjusted for the other effects of the model. Incorporating the TED parameter with other model components will give us an adjusted TED effect, taking into account, for example, long-term trends in strandings due to loggerhead population decline.

To account for the one or more periodicities in the data, terms such as $R_i \cos(2\pi\omega_i t + \phi_i)$ are typically used. Here R_i and ϕ_i are the amplitude and phase of the ith sinusoid. In our case, we assume that the frequencies, ω_i, are known and taken to be 1/16, 2/16, and 3/16 representing annual and semiannual effects of turtle movements and other seasonal effects. Making use of the trigonometric identity

$$R_i \cos(2\pi\omega_i t + \phi_i) = A_i \cos(2\pi\omega_i t) + B_i \sin(2\pi\omega_i t)$$

gives us the parameterization shown in the regression model. This allows fitting to be done by least-squares where estimates can be obtained for A_i and B_i rather than the R_i and ϕ_i.

The regression model was fit by ordinary least-squares using PROC REG (Statistical Analysis Systems Institute, Inc., Cary, NC). However, the residual variance was not constant, being roughly proportional to the number of strandings. That is, in years of high strandings, the variance appears to be much higher than in other years. This occurrence is common when analyzing count data and typically can be rectified by log-transforming the dependent variable. The model was refit to the log (strandings + 1), and a residual plot indicated reasonably homogeneous error variance.

A further assumption of the regression model is that the ϵ_t are independent. Violation of this assumption can be assessed by examining the autocorrelation function (ACF) and the partial autocorrelation function (PACF) of the residuals. Examination of these indicated significant correlation among the residuals. To produce valid standard errors for the parameter estimates of model fit to the log strandings, the dependence among the residuals must be accounted for.

A class of models that is useful for correlated data are the ARMA models, (Box and Jenkins, 1976), and we have chosen to model the residuals, ϵ_t, from model as an ARMA process. An autoregression model in the most basic form [AR(1)] has the current value of Ut (the residuals from the regression model in our case) depending on the previous value, U_{t-1}, as

$$U_t = \rho U_{t-1} + v_t$$

where v_t is uncorrelated random error. The most basic form of a moving-average model [MA(1)] is,

$$U_t = v_t + \alpha v_{t-1}$$

That is, U_t depends on the previous residual.

Examining various models from the ARMA class in PROC ARIMA (Statistical Analysis Systems Institute, Inc., Cary, NC) indicated that an MA(1) model from this class produced the most parsimonious fit, and the residuals from this model showed no significant autocorrelation. This is examined by plotting the autocorrelations for various lag distances and is formally tested using the Box-Pierce Q-statistic (Box and Jenkins, 1976).

The estimates and standard errors from regression model fit to the log strandings using PROC ARIMA are given in Table 2. To produce valid hypothesis tests of parameter values the assumption of normally distributed errors is made. This assumption can be examined by plotting the quantiles of the residuals vs the quantiles of the standard normal distribution and is easily tested using the Anderson-Darling Goodness-of-Fit test with unknown parameters (Stephens, 1976).